

Analysis of a Stretched Derivative Aircraft with Open Rotor Propulsion

Jeffrey J. Berton, Eric S. Hendricks and William J. Haller
NASA Glenn Research Center, Cleveland, Ohio 44135

and

Mark D. Guynn
NASA Langley Research Center, Hampton, Virginia 23681

Research into advanced, high-speed civil turboprops received significant attention during the 1970s and 1980s when fuel efficiency was the driving focus of U.S. aeronautical research. But when fuel prices declined sharply there was no longer sufficient motivation to continue maturing the technology. Recent volatility in fuel prices and increasing concern for aviation's environmental impact, however, have renewed interest in unducted, open rotor propulsion and revived research by NASA and a number of engine manufacturers. Recently, NASA and General Electric have teamed to conduct several investigations into the performance and noise of an advanced, single-aisle transport with open rotor propulsion. The results of these initial studies indicate open rotor engines have the potential to provide significant reduction in fuel consumption compared to aircraft using turbofan engines with equivalent core technology. In addition, noise analysis of the concept indicates that an open rotor aircraft in the single-aisle transport class would be able to meet current noise regulations with margin. The behavior of derivative open rotor transports is of interest. Heavier, "stretched" derivative aircraft tend to be noisier than their lighter relatives. Of particular importance to the business case for the concept is how the noise margin changes relative to regulatory limits within a family of similar open rotor aircraft. The subject of this report is a performance and noise assessment of a notional, heavier, stretched derivative airplane equipped with throttle-push variants of NASA's initial open rotor engine design.

I. Introduction

Fluctuating fuel prices and concerns over carbon emissions are spurring research into advanced, energy-efficient propulsion concepts for transport aircraft. As a result, rekindled attention is being given to open rotor propulsion systems. Once hailed as an innovative response to the sharp increases in aviation fuel cost beginning in 1973, interest in open rotors waned in the face of falling oil prices starting in 1986. Current energy concerns are reviving development efforts into open rotor propulsors (alternately known as advanced turboprops, propfans, or unducted fans).

Counter-rotating open rotor propulsion systems – with highly-swept, contoured, wide-chord rotor blades – combine the fuel efficiency of traditional turboprops with the high cruising airspeed of turbofan engines. Without inlet and bypass exhaust ducts, however, a disadvantage of the open rotor relative to ducted turbofans appears to be higher levels of community noise. Despite this handicap, a notional open rotor

single-aisle airplane jointly-studied by NASA and General Electric is currently projected to enjoy a Chapter 4 cumulative margin of nearly 17EPNdB (Refs. 1, 2). Moreover, the open rotor transport is predicted to burn 36% less block fuel than a 1998 technology reference vehicle equipped with turbofans (Ref. 1).

Although this is an exciting and promising result, these noise margin predictions require further study. Of particular importance is the behavior of community noise within a family of similar aircraft. Certification noise levels tend to increase when a propulsion system undergoes a "throttle push" thrust increase and is coupled with a heavier derivative aircraft in the same family. If heavier, derivative open rotor transports do not have similarly comfortable noise margins, it may become difficult to develop a compelling economic argument for the concept.

The subject of this report is a performance and noise examination of a throttle-pushed open rotor engine variant coupled with a heavier derivative aircraft carrying additional payload. This assessment builds on

earlier NASA open rotor transport studies documented in References 1, 3, 4, and 5.

II. Method of Analysis

For brevity, the reader is referred to our earlier reports for more detailed information. Our most recent results using General Electric's "Generation 2" rotor design can be found in Ref. 1. Details regarding the engine thermodynamic cycle analysis, aeromechanical design, flowpath and weight analysis of the open rotor powerplant, as well as the vehicle and noise analyses, can be found in Ref. 3. Briefly, however, the propulsion system is modeled at NASA using the Numerical Propulsion System Simulation code (Refs. 6, 7). NPSS is an engine cycle analysis tool developed jointly by NASA and U.S. industry. It is currently the accepted, state-of-the-art software for airbreathing engine cycle performance analysis for U.S. aerospace industry, academia, and NASA. Rotor performance is represented in the NPSS model via thrust coefficient and power coefficient propeller maps. These maps are based on wind tunnel performance tests (conducted in NASA Glenn's 9- by 15-ft and 8- by 6-ft wind tunnels) of General Electric's advanced, Generation 2 open rotor test articles (Ref. 8).

Aeromechanical design, flowpath, and engine weight analyses are performed using additional elements coded within NPSS. NPSS provides a complete modeling capability of gas turbine engines. A summary of NASA's open rotor engine characteristics is shown in Table 1. A solid model of the open rotor propulsion system is shown in Figure 1.

Table 1. NASA open rotor engine summary (reproduced from Ref. 1).

Front rotor diameter, ft	13.5
Thrust (Sea level, static, ISA+27°F), lb	27810
Specific fuel consumption (M0.78/35kft/ISA), lb/hr/lb	0.415
Overall pressure ratio (M0.78/35kft/ISA)	42
Maximum combustor exit temperature, °R	3460
Total engine pod weight, lb	9365

NASA's notional, advanced single-aisle transport airframe model accommodates 162 passengers in mixed-class seating. It is equipped with open rotor engines mounted on the rear of the fuselage. Vehicle sizing and mission performance are assessed using the methods described in Refs. 1 and 3. A solid model of the airplane is shown in Figure 2.

Certification noise predictions are made using noise measurements of the Generation 2 open rotor test articles collected in the NASA 9- by 15-ft Low Speed Wind Tunnel. A more detailed explanation of how these noise measurements are processed, scaled to full size, and projected to flight conditions is described in our earlier reports. The open rotor noise sources (as well as other propulsion and airframe noise sources) are

analytically flown along a trajectory and propagated to noise certification monitors on the ground using NASA's Aircraft Noise Prediction Program (ANOPP, Refs. 9, 10).

A. Engine design and operating considerations

An engine must deliver sufficient thrust to satisfy an airplane's performance requirements throughout its flight envelope. It is sometimes feasible to design an engine cycle that precisely matches the airplane's thrust demand at altitude, at sea level, and at other flight conditions in between. Turbomachinery design variables, operating temperatures, pressures and airflows may be selected so that the engine delivers required thrust levels at multiple design points.

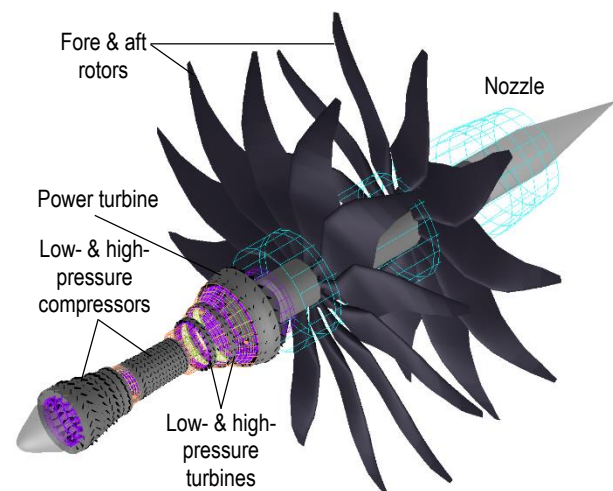


Figure 1. Solid model of NASA's notional open rotor propulsion system.



Figure 2. NASA's notional, advanced single-aisle transport airplane equipped with fuselage-mounted open rotor engines.

But often, practical considerations make this approach impossible. An attempt was made to design NASA's open rotor propulsion system (Ref. 1) to exactly match the airplane's thrust demand at the end of its takeoff ground roll and at the top of its climb path. The turbine temperatures at altitude required to match these targets were discovered to be excessively hot. Indeed, for engines with very low specific thrust (such as an open rotor or a turboprop engine), it is possible for turbine temperatures at altitude to be uncomfortably close to the maximum temperatures used at takeoff. The burner temperature in the final design was reduced over concerns for hot section life. The result of this decision is an engine that satisfies airplane climb requirements, but has *more* than enough thrust available for takeoff.

Thus, unlike most turbofan airplanes, an open rotor airplane would likely be constrained by performance requirements at top-of-climb, not by field length or by other takeoff or landing considerations near sea level. Much like a turboprop airplane, there is typically plenty of thrust available at takeoff to meet any reasonable field length requirement. An open rotor engine would perhaps be sized by the airplane's potential rate of climb at its service ceiling for a maximum gross weight mission. In our assessments, our open rotor airplanes are required to have a minimum potential climb rate of 300ft/min at the 35kft initial cruise altitude.

The open rotor propulsion system developed in Ref. 1 is subjected to a "throttle push." A throttle push is a change made to an engine that provides the additional thrust required for a heavier derivative airplane. In this study, the changes made to the engine are operational only – there is no redesign of any engine component relative to its original configuration. The original engine cycle design is assumed to have sufficient margins built into it to accommodate any new operational changes.

The engine cycle operation is constrained by hot-section temperature limits near sea level, and by spool speed limits at altitude. The active constraint changes from the former to the latter at some point during the climb from takeoff to cruising altitude. An engine throttle push may be achieved by relaxing the maximum hot section temperature constraint (i.e., "overtemping") near sea level and/or by relaxing the maximum rotational rates of the spools (i.e., "overspeeding") at altitude. The former approach results in more thrust at takeoff, while the latter results in more thrust at altitude.

For a heavier derivative open rotor airplane, extra thrust should always be necessary at altitude to maintain service ceiling performance and the initial cruise altitude requirement. However, given the open rotor engine's excellent low-speed thrust performance, extra thrust may *not* be needed for takeoff unless the field length requirement grows too much. Thus, two throttle

push options emerge, and each is investigated in this study:

B. Throttle push option 1

In this scenario, the open rotor engine is required to overspeed at altitude. The maximum low-pressure spool speed limit is allowed to increase by five percent. The engine is *not* overtemped near sea level. This results in more thrust at altitude, but the thrust near sea level is unchanged. Since the derivative airplane is heavier, the most important consequences of this approach are longer takeoff field lengths and climbout rates. But field lengths for open rotor-powered transports are already shorter than comparable turbofan-powered transports, so an increase in field length may be acceptable. Further, if overtemping the open rotor cycle is unnecessary, its hot-section life characteristics would not worsen.

C. Throttle push option 2

This option is similar to how a conventional turbofan manufacturer might approach the problem. The open rotor engine is allowed to overspeed at altitude and to overtemp near sea level. A five percent increase in the maximum low-pressure spool speed and a 50°F increase in the maximum combustor exit temperature are assumed. This option results in more thrust everywhere. With the increased temperature, there would be an impact on hot-section life and engine maintenance. But this option may be necessary only if the airplane becomes too heavy and the takeoff field length grows too much.

III. Results and Discussion

The higher maximum spool speed limit used in both throttle push options results in additional thrust at altitude. This additional top-of-climb thrust may be exploited and used to design a heavier derivative transport with a useful increase in maximum gross weight and payload weight.

A. Derivative airplane design

There is no clear convention for designing a derivative aircraft type. Passenger airline operators have route structures requiring equipment capable of flying variable payload weights, fuel loads, seats, and ranges. As such, airframe manufacturers build derivative types to try to satisfy a variety of customer needs. Insight into derivative type design can be gained from examining evolutionary trends within the 737NG transport series. Maximum gross weight, maximum payload weight, number of seats, fuel capacity and range vary across the 737-600, -700, -800 and -900 family. In most cases, the maximum payload weight increases as the number of seats increase. Also, the range capability at the design payload weight tends to decrease as the number of seats increases. Another observation is that the maximum fuel capacity does not change from model to model.

There are no definitive rules for designing a stretched derivative, but our process must begin somewhere. One prerequisite is to determine roughly how many additional rows of seats can be added to the derivative open rotor transport given the increase in thrust at the top of climb condition. When additional seat rows are added (with five seats abreast at 200lb per passenger), the payload weight increases by 1000lb per row. The following steps are taken: 1) passengers are added one row (i.e., five passengers) at a time and the fuselage is analytically stretched; 2) the additional fuselage weight, system weights and drag are computed; and 3) the takeoff gross weight is estimated. For each row of passengers added, a new service ceiling thrust requirement is computed. The process is repeated – one row of passengers at a time – until the service ceiling thrust required exceeds the engine thrust available.

In the end, our notional derivative transport is assigned an additional four rows with an increase in payload weight of 4000lb. The original interior provides for 162 passengers in mixed-class, 4/5 abreast seating (12 seats on 36-inch pitch, 14 seats on 32-inch pitch, and 132 seats on 31-inch pitch). The derivative interior provides for 182 passengers with 152 seats on 31-inch pitch. Sketches of the interior arrangements of the original and the stretched derivative are shown in Figure 3. The additional four rows of seats are colored in red.

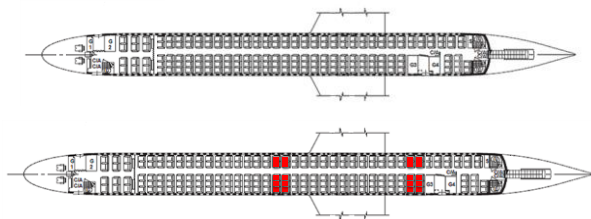


Figure 3. Sketches of original (top) and derivative (bottom) interior arrangements.

With this information in hand, the following steps are used to more rigorously design the heavier derivative open rotor transport:

- 1) The maximum payload weight and the design payload weight are increased by 4000lb.
- 2) The maximum fuel capacity remains constant.
- 3) The maximum gross weight is determined by a sizing process (Ref. 3) while ensuring at least a 4000lb increase in the available payload weight for the maximum fuel, maximum gross weight mission.

The wing design is unchanged during this process. Analysis tools and assumptions described in our earlier reports are used. The resulting payload-range diagrams of the original and derivative transports are shown in Figure 4. The result of this approach is that the differences between the payload-range curves of the derivative and original transports are similar to changes in the curves within the 737NG family.

A comparison of the original transport and its derivatives is shown in Table 2. The derivatives, with 20 additional passengers, are more than ten thousand pounds (eight percent) heavier in maximum gross weight than the original type. By the measure of available seat miles per unit fuel burned, the derivatives are approximately five percent more efficient than the original type at maximum gross weight and maximum payload.

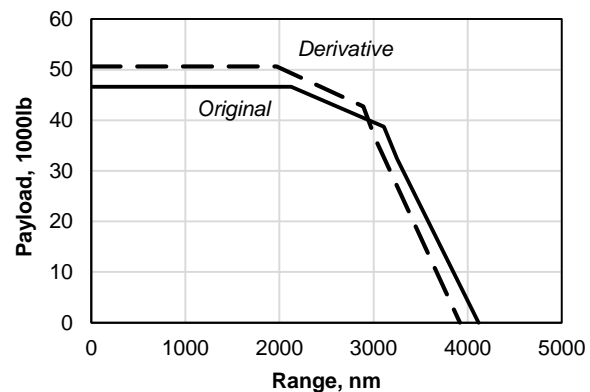


Figure 4. Payload-range diagrams of the original and derivative transports.

Table 2. Original and derivative type comparison.

	Original	Option 1	Option 2
Passengers	162	182	182
Max payload wt, lb	46,640	50,640	50,640
Sea level static thrust, lb	30,310	30,310	31,330
Operating empty wt, lb	91,260	97,460	97,460
Max gross wt, lb	161,080	171,300	171,300
Takeoff field length, ft	6200	7310	6800
Climb rate (35kft), ft/min	300	416	416

For the derivative with throttle push option 1 (where the engines are not overtemped and the thrust near sea level is unchanged), the FAA Part 25 takeoff field length (standard day plus 27°F at sea level) increases from 6200ft to 7310ft. This 1110ft increase in takeoff field length is, however, smaller than penalties experienced by other stretched derivatives, such as the 2800ft takeoff field length increase for the 737-900ER compared to the 737-800 (Ref. 11). Overtemping the engine (via throttle push option 2) mitigates the increase in field length. But given the open rotor engine's excellent low-speed thrust performance, overtemping the engine may not always be necessary.

The open rotor engines for the original transport are sized by an initial cruise altitude capability for a mission beginning at maximum gross weight. This is determined requiring a service ceiling defined by a minimum potential climb rate of 300ft/min at M=0.78 and 35kft. For the derivative types using engine overspeed, the potential rates of climb are better than the original. This

suggests that a throttle push using less spool overspeeding may be possible.

B. Takeoff and approach analysis:

Airplane trajectories and engine operating conditions have an important influence on certification noise. The two derivatives are heavier than the original airplane. And the overtemped engine (using throttle push option 2) has additional thrust available near sea level. The result is that all three airplane types behave differently during takeoff and approach. The trajectories and engine throttle setting histories for each airplane are evaluated using the assumptions and methods discussed in Ref. 3 and abide by FAA Part 36 regulations.

Trajectory data evaluated for a sea level field at 77°F are shown in Figure 5. Altitude above field elevation, true airspeed, and true thrust per engine are plotted against the distance from brake release. The trajectories are shown with takeoff and landing operations superimposed. For presentation purposes, the touchdown point on landing is coincident with the point of brake release on takeoff. The noise abatement engine power cutback is completed at approximately 17,000ft from brake release. On approach, a three-degree glide slope is followed, the maximum landing weight is assumed, and the flaps, leading edge slats and landing gear are deployed. The engine thrust is set to a level that maintains a stable three degree glide slope.

The triangular markers on each plot denote noise certification measurement locations. A sketch of the noise monitor arrangement relative to the takeoff and landing flight paths is shown in Figure 6. The approach microphone markers are shown in the figures at 6562ft behind the runway threshold, and approximately 7518ft behind the instrument landing system touchdown zone on the runway centerline. The monitor is located under the point of the approach path where the airplane is 394ft above ground level. The lateral microphone locations lie along a sideline parallel to the runway displaced 1476ft from the extended runway centerline. They are arranged along the sideline across from the locations where the airplanes reach an altitude of 1000ft above the field elevation (i.e., the point where ground attenuation effects diminish and where maximum lateral noise is typically observed). The flyover microphone markers are shown in the figures at 21,325ft from brake release on the extended runway centerline. Airspeed, altitude and thrust per engine for the three airplane types at each noise monitor are shown in Table 3.

C. Noise analysis:

The following observations are made from the trajectory assessment above. Each effect is responsible for changes in noise relative to the original type:

- 1) The heavier derivative airplanes do not reach altitude as quickly as the original type.

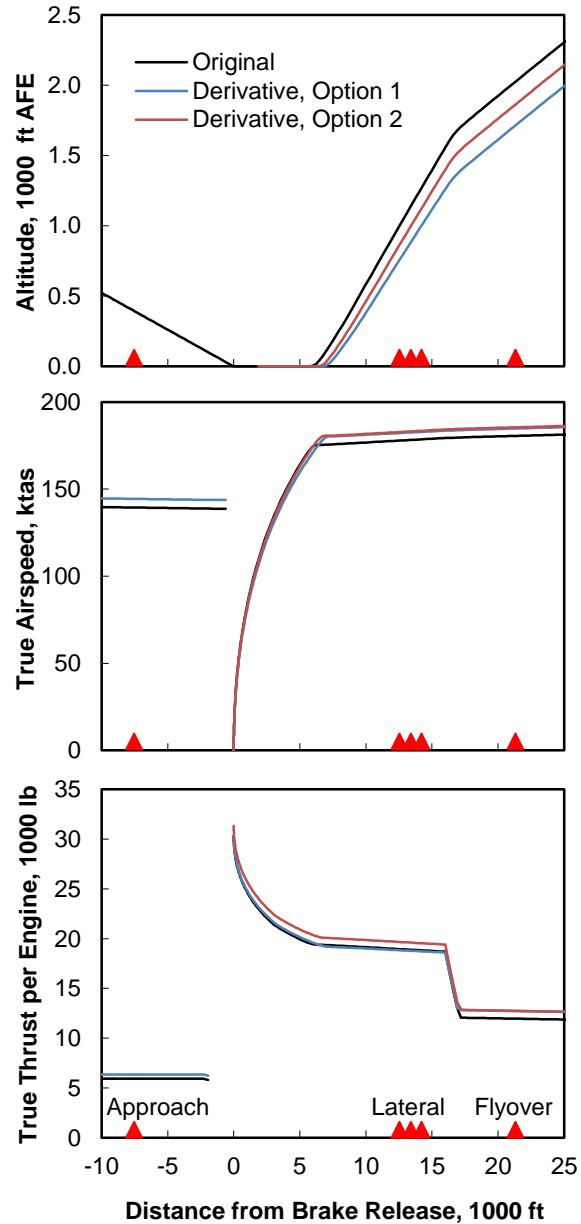


Figure 5. Comparison of altitude, airspeed and thrust per engine during takeoff and approach.

Table 3. Original and derivative trajectory information at noise monitor locations.

	Original	Option 1	Option 2
<i>Approach:</i>			
Airspeed, ktas	139	144	144
Altitude, ft	394	394	394
Thrust per engine, lb	5926	6359	6359
<i>Lateral:</i>			
Airspeed, ktas	178	183	183
Altitude, ft	1000	1000	1000
Thrust per engine, lb	18,940	18,720	19,600
<i>Flyover:</i>			
Airspeed, ktas	181	185	185
Altitude, ft	2030	1710	1860
Thrust per engine, lb	11,960	12,740	12,730

- 2) The heavier derivatives require additional airspeed before rotating. Since thrust lapses naturally with airspeed, the engine thrust for the derivative with throttle push option 1 is less than the original type, despite having identical engine performance in general near sea level.
- 3) The derivative with overtemped engines (throttle push option 2) has the highest maximum thrust.
- 4) The heavier derivatives cannot reduce engine thrust as much as the original type during noise abatement cutbacks. This is a result of minimum climb gradients required by FAA Part 36 regulations.
- 5) The derivatives, with heavier maximum landing weights, require slightly more thrust and have higher airspeed on approach.

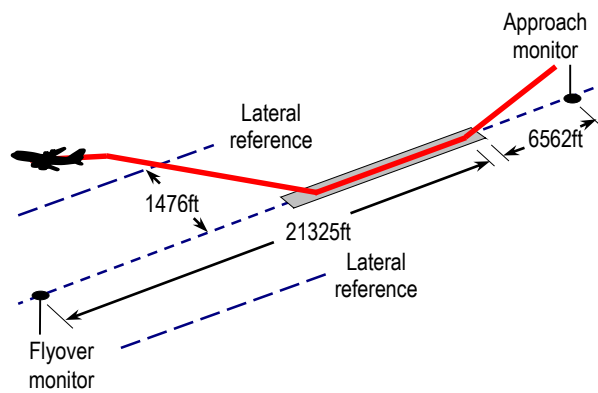


Figure 6. Noise certification monitor arrangement relative to takeoff and landing flight paths.

Table 4. Original and derivative EPNLs with cumulative margins relative to Chapter 4 and Chapter 14 limits (in EPNdB).

	Original	Option 1	Option 2
Approach	89.5	89.9	89.9
Lateral	90.1	89.9	90.9
Flyover	82.2	84.4	83.7
Cumulative	261.8	264.2	264.5
Ch 4 cumulative margin	16.8	15.2	14.9
Ch 14 cumulative margin	9.8	8.2	7.9

Effective Perceived Noise Levels (EPNLs) are calculated using the methods and tools discussed in our earlier reports. The trajectories and engine thrust levels of the new derivative transports result in noise changes relative to the original type. The results and cumulative margins relative to current Chapter 4 and future Chapter 14 limits are shown in Table 4. Chapter 14 limits for this aircraft size are expected to debut on December 31, 2017. Although these EPNLs are computed using the best available data and analytical methods, they should be regarded with some skepticism. Projecting acoustic measurements from a subscale open rotor test article to flight conditions at full-scale (and further projections

from concept to product) has some inherent, unknown error. An analysis of this uncertainty is beyond the scope of this report.

Results indicate the derivative transport with engine overtemping and overspeeding (option 2) has a higher lateral EPNL than the original transport, given its higher maximum thrust. But the derivative with engine overspeeding only (option 1) has a higher flyover EPNL, owing to its lower flyover altitude. These effects tend to be offsetting. Thus, certification noise levels on a cumulative basis are nearly identical for both throttle push options. There does not seem to be a preference for either engine throttle push strategy, at least in terms of the cumulative noise margin.

The open rotor noise results are shown graphically in Figure 7. Also plotted in the Figure are all 737NGs equipped with CFM56-7B27 series turbofans. As of March 2014, 1044 of these types have been issued noise certificates. These particular 737s are of interest since they are all derivative types with variable passenger counts and/or freight capabilities, maximum gross weights and ranges, and they would compete in the same market as our open rotor transports. Further, they are all equipped with the CFM56-7B27, which delivers the same thrust performance to all of the derivative types. Thus, the trends of noise with maximum takeoff gross weight of these 737s should be well-suited to compare with our original open rotor transport and its option 1 derivative. The option 2 derivative is not plotted since its thrust near sea level is higher than the original type and it would not be consistent with the 737 data shown.

Regression lines are shown for each transport family. The cumulative noise levels for the subset of 737 data are found to vary with a slope of 52 times the logarithm of the maximum takeoff gross weight. By way of comparison, ICAO has estimated the slope to be 67, on average, across all aircraft and turbofan engine families (Ref. 12).

Of particular interest is the slope of flyover noise relative to gross weight. The flyover noise of open rotor transports appears to increase with increasing weight more quickly than the noise of the selected 737s. Open rotor engine thrust lapses more quickly with airspeed than comparable turbofans. It may be that open rotor transport families are not able to fly as high over, nor able to cut back thrust as deeply at the flyover noise monitor point as a comparable family of turbofan transports. On a cumulative basis, the open rotor transports are found to vary with a slope of 91. In a comparison made by ICAO (Ref. 12), the slope of open rotor transports was estimated to be 74, based on a study conducted by Airbus and using our own, earlier results.

The slope of the regulatory limits with gross weight has further implications. Chapter 3 noise limits are plotted in the Figure for each of the three noise

measurement locations. The Chapter 4 cumulative limit for twin-engine transports is plotted along with the cumulative noise data. The flyover, approach and cumulative noise margins of open rotor transports appear to erode more quickly with increasing gross weight than comparable turbofan-powered transports. The slopes with respect to maximum gross weight of the open rotor and 737 transports relative to the limits are labeled in the Figure.

IV. Conclusions

Two approaches for throttle-pushing a notional open rotor engine are described. In one, the maximum takeoff combustor temperature is kept the same as the original engine type (option 1), while in the other it is increased to provide additional thrust near sea level (option 2). In both, the maximum spool speed limit is increased to provide more thrust at altitude. The throttle-pushed engines are used to analytically design stretched-derivative transports that are larger and heavier than the open rotor transport described in our earlier reports.

Overtensing the engine (via throttle push option 2) mitigates increases in takeoff field length incurred by heavier transports. But given the open rotor engine's excellent low-speed thrust performance, field lengths are nevertheless shorter than many comparably-heavy 737s. Overtensing an open rotor engine to obtain additional thrust for takeoff may not always be necessary. In that case, engine hot section life and

maintenance requirements for throttle-pushed open rotor systems could be similar to the original engine type.

Further, there appears to be no preference for either of our throttle-push methods insofar as cumulative noise margin is concerned. A derivative equipped with engines using option 1 results in higher flyover noise than the original type, while a derivative with engines using option 2 results in higher lateral noise. The resulting cumulative noise margins for the derivatives are nearly identical.

Last, these calculations indicate that the noise margins of a family of open rotor transports may erode more quickly with increasing takeoff gross weight than margins of comparable families of turbofan transports. The more aggressive Chapter 14 limit may constrain growth versions of open rotor transports, particularly if our open rotor noise levels are underpredicted or if very large derivatives are desired.

Acknowledgements

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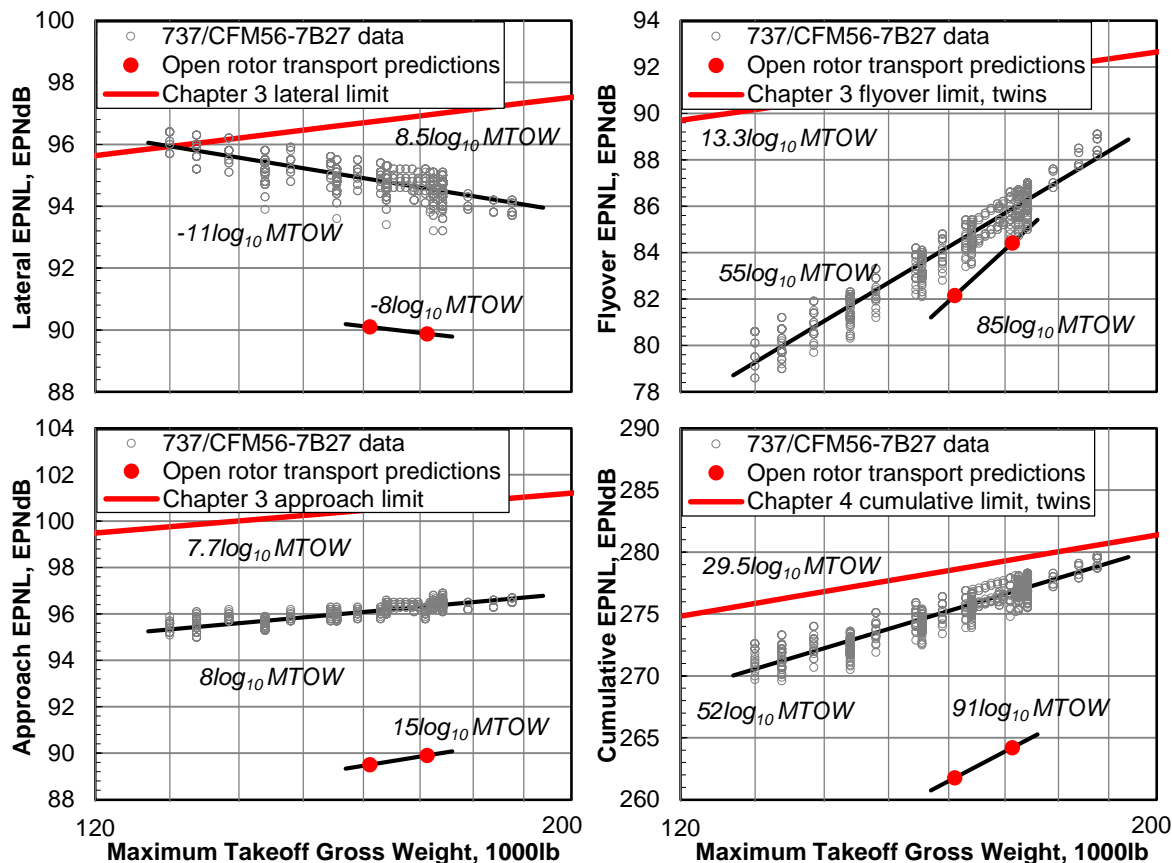


Figure 7. Dependency of noise on maximum gross weight: certification noise predictions of original open rotor transport and a derivative equipped with engines using throttle push option 1, compared with all 737NGs equipped with CFM56-7B27 series turbofans.

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